Defense Technical Information Center Compilation Part Notice

This paper is a part of the following report:

- *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention. Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

- *To order the complete compilation report, use:* AD-A325 558

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

METALLURGICAL EXAMINATION OF A FAILED SPIRAL BEVEL GEAR

Marc Pepi
U.S. Army Research Laboratory
Materials Directorate
Aberdeen Proving Ground, Maryland 21005

Abstract

A failed spiral bevel transmission gear from an Army cargo helicopter was first sent to the primary contractor for analysis and then the Army Research Laboratory. The failure occurred during a training flight at Ft. Meade, Maryland, where a reported "loud bang and shutter" forced an immediate landing. Subsequent inspection of the Number 2 engine revealed a 15-20 degree section of the gear had fractured and penetrated the transmission housing. The gear was fabricated from X-2M steel, a high hot hardness alloy. Light optical microscopy of the failed gear section revealed characteristics consistent with a fatigue failure, including a relatively flat fracture surface and beach marks. The fracture origin was located at a defect characterized by a darkened half-moon shaped region. The darkened topography was considered evidence that a pre-existing crack was present during the manufacturing process of the gear. Energy dispersive spectroscopy of the blackened surface revealed the presence of sodium, indicating the crack was open to the black oxide finish process. The pre-existing crack was oriented perpendicular to the direction of grinding, indicating the possibility of a grinding crack. Metallography confirmed that a pre-existing crack was a grinding burn, since evidence of rehardening and retempering were observed. Also a possible contributory factor to crack propagation was the presence of a carbide network in the carburized case of the X-2M steel part. Metallographic examination of the damping ring groove area (fracture origin location) showed a deeper than acceptable carburized case. It was later learned that this region was not masked, and was subject to a double carburization by mistake. Further visual examination of the failed component revealed small grinding cracks at the corner of the tapered surface. Although the morphology of the origin was featureless, fractographic examination of a secondary fracture (most likely an additional grinding crack) did reveal an intergranular "rock-candy" morphology. This was evidence that the crack propagated along the carbide network. It was concluded that the double carburization sequence of the damping ring groove section led to the formation of carbide networks within the carburized case. This scenario created a very hard surface, rendering it sensitive to grinding. Improvements have since been added to the manufacturing sequence including an additional magnetic particle inspection to determine the existence of cracks and nital etch inspection to locate possible grinding burns. In addition, the grinding process for burr removal in the damping ring groove region had been replaced with a less detrimental turning process. Also, the manufacturer has agreed to consider an addition to the material specification which would include micrographs of unnacceptable case microstructures.

Key Words: Carbide networks; Carburization; Failure analysis; Metallurgical examination; Spiral bevel gear; X-2M steel.

Background

A spiral bevel transmission gear (Figure 1) from an Army cargo helicopter failed during a training flight leading to an immediate landing. Inspection of the number 2 engine transmission revealed that an 8-tooth segment (out of a 35-tooth gear) had fractured and penetrated the transmission housing. The failed component was fabricated from X-2M steel (a modified H11 tool steel), and

carburized to a required case hardness of 59-64 HRC. The broken parts were subject to visual examination/ light optical microscopy, magnetic particle inspection, chemical analysis, metallography, hardness testing/case depth measurement, X-ray diffraction, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Transmission electron microscopy/striation counts of the failed part were performed by the contractor.

Visual Examination/Light Optical Microscopy

Visual examination and light optical microscopy of the fracture surfaces revealed characteristics consistent with a fatigue failure, including smoothness of fracture and beach marks (Figure 2). The beach marks and radial lines on the fracture surface revealed that the origin was located in the damping ring groove portion of the gear at a darkened half-moon shaped defect (Figure 3). The pre-existing crack was oriented perpendicular to the direction of grinding, suggesting the possibility of a grinding crack. The darkened region had a featureless topography resembling that of a steel surface which has been exposed to a heat treatment atmosphere. Energy dispersive spectroscopy (EDS), in conjunction with a scanning electron microscope (SEM), within the darkened area revealed the presence of sodium. This finding was considered evidence that a pre-existing crack was present during the manufacturing process, since sodium nitrate and sodium dichromate are widely used to black oxide finish steel components. EDS spectra outside this darkened region failed to detect the presence of sodium. Further visual examination and magnetic particle inspection of the remaining component revealed small grinding cracks located in the same area as the fracture origin.

Magnetic Particle Inspection

Magnetic particle inspection was performed by the contractor on the failed part before sectioning. Several small grinding cracks were noted emanating from the damping ring groove region. The surface length of the cracks ranged from 0.015-0.025 inch.

Chemical Analysis

The elemental composition of the X-2M steel was analyzed to determine conformance to the governing specification. The carbon content was determined by infrared detection combustion, while the sulfur was automatic titration combustion. The contents of the remaining elements were determined through direct current plasma emission spectroscopy. The molybdenum content was slightly lower than specified, however, the remaining elements conformed to the governing specification. Table I lists the results of this analysis.

Table I
Chemical Analysis
Weight Percent

	C	Si	Mn	S	P	W	Cr	V	Mo	Fe
Gear	0.15	0.86	0.28	<0.001	<0.004	1.33	5.17	0.42	1.25	Rem
Specification	0.13-0.16	0.80-1.10	0.20-0.40	0.010 max.	0.015 max.	1.20-1.50	4.75-5.25	0.40-0.50	1.30-1.50	Rem

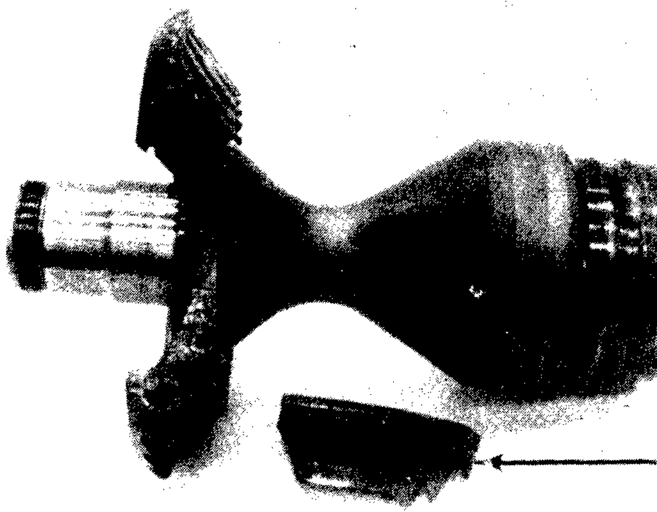

Figure 1 Optical Macrograph of the failed spiral bevel gear and the fractured eight-tooth segment (denoted by the arrow). Reduced 70%.

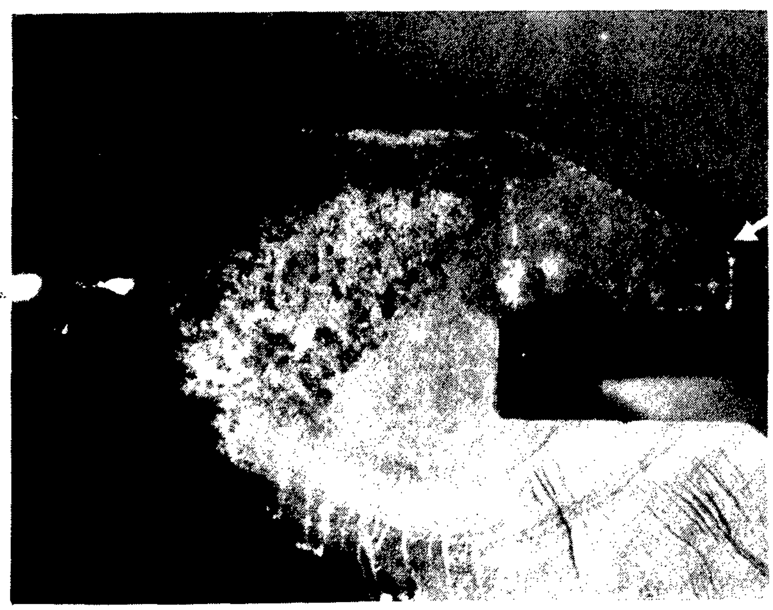

Figure 2 Optical micrograph of the primary fracture surface showing evidence of fatigue (beach marks). Arrow denoted fracture origin. Mag. 7.5x.

Metallography

A sample was sectioned through the origin and metallographically prepared to confirm that the pre-existing defect was a grinding crack. The sample showed evidence of rehardening (white region) and retempering (dark region) as shown in Figure 4. This pre-existing crack was oriented perpendicular to the direction of grinding, consistent with a grinding crack. Other grinding burns and grinding cracks were also noted adjacent to the fracture origin. In addition, metallography revealed what appeared to be continuous carbide networks (CCN's) in the region of the gear which contained the origin (Figure 5). These networks were discontinuous in high stress areas, such as the gear root and flank. Continuous carbide networks are generally caused by an excessive carbon potential during the carburization process, and can act to embrittle the case and reduce the fatigue limit of the component under bending fatigue conditions. Also, these networks render a surface sensitive to grinding, and if cracking occurs, it usually follows the path of the networks. Metallography combined with microhardness testing of the damping ring groove area (fracture origin location) revealed a greater case depth than specified (see Hardness/Case Depth Measurement section for results). The core structure was consistent with the prior treatment (duplex structure of free ferrite within tempered martensite).

Hardness/Case Depth Measurement

The case hardness was measured directly from a section of the component. The hardness was measured utilizing the superficial Rockwell 15-N scale, since the lighter major load (15kg) posed less of a risk of penetrating the case depth compared to the major load of the Rockwell "C" scale (150kg). The depth of the HR15-N hardness indentations was calculated to ensure the 15kg load did not penetrate the case and measure a composite of both the case and the core. The depth of penetration of the HR15-N diamond indenter was calculated from the following formula [1]:

$$(100\text{-HR15-N}) \times 0.001\text{mm} = \text{depth of penetration}$$

Applying this formula, a hardness of 88.9 HR15-N (the lowest reading measured) had a depth of penetration of 0.00044 inch which was safely within the required case depth of 0.030-0.050 inch. The readings were subsequently converted to the Rockwell "C" scale using standard conversion charts. Table II lists the results of case hardness testing. The average converted HRC measurement (61 HRC) conformed to the governing requirement of 59-64 HRC.

Table II
Case Hardness Measurements
HR15-N Scale
Major Load 15kg

Reading	HR15-N	Eq. HRC	
1	90.0	60	
2	88.9	57	
3	90.1	60	
4	91.0	62	
5	90.1	60	
6	90.6	61	
7	91.1	62	
8	92.4	66	
9	91.5	63	
10	90.3	60	
Average	90.6	61	Required 59-64

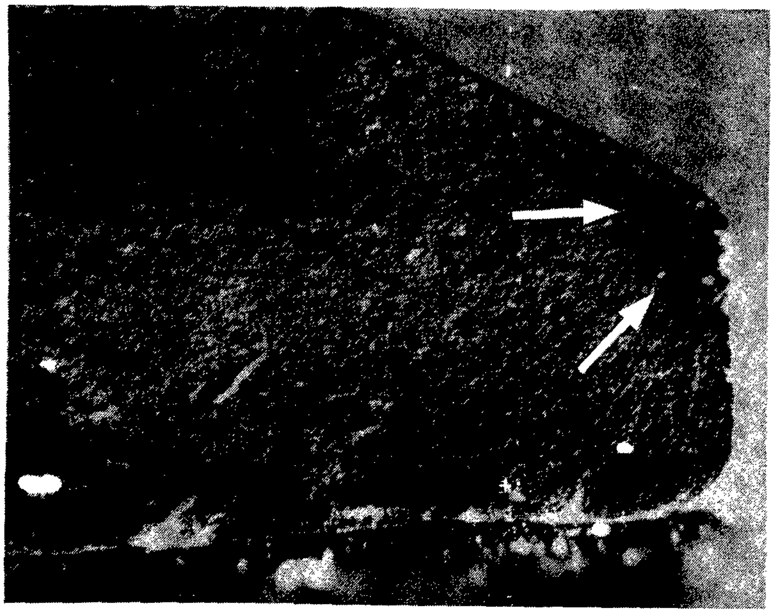

Figure 3 Magnified view if the processing defect at the origin. The grinding crack is denoted by arrows. Mag. 40x.

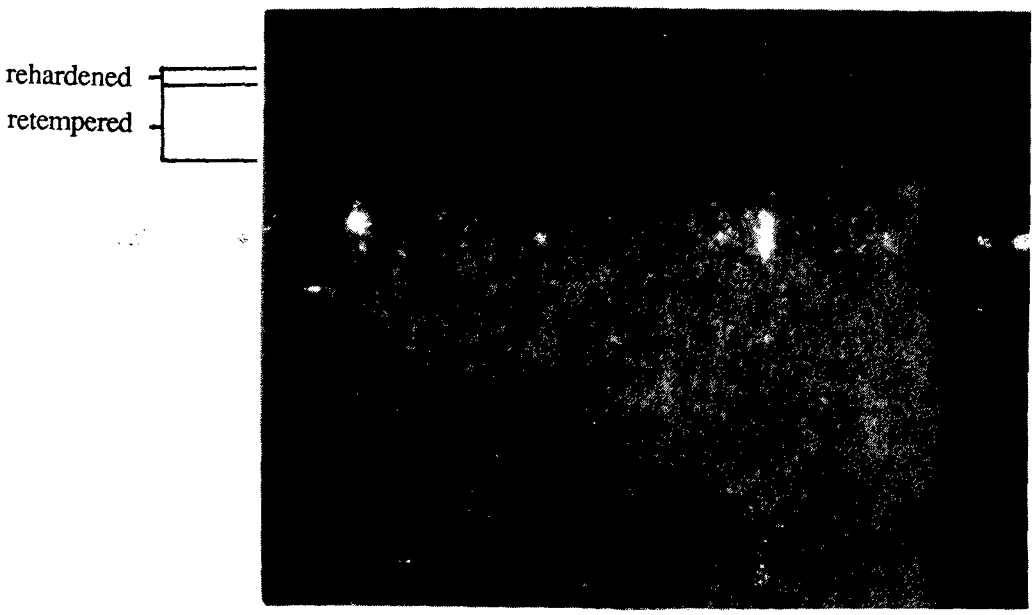

Figure 4 Metallographic section through the origin. Note the rehardened white layer, and the retempered darkened layer caused by the grinding burn. Mag. 200x.

The core hardness was measured utilizing the Rockwell "C" scale. A total of four sections were analyzed. The results are listed in Table III. Each reading conformed to the governing requirement of 36-44 HRC.

Table III
Core Hardness Measurements
HRC Scale
Major Load 150kg

Reading	Section 1	Section 2	Section 3	Section 4	
1	38.7	38.7	40.4	39.6	
2	38.7	39.2	40.5	40.4	
3	38.8	40.6	40.2	40.5	
4	38.6	40.2	40.7	40.2	
5	38.3	39.8	41.0	40.5	
6	39.7	40.3	40.7	40.7	
Average	38.8	39.8	40.6	40.3	Required 36-44

The effective case depth was measured from four metallographically prepared samples. Three samples represented gear tooth roots, and one sample represented the damping ring groove region. The case depth was defined as the perpendicular distance from the surface to a point where the microhardness of the part was 513 VHN (approximately 50 HRC). The case depths were measured directly from photomicrographs taken at 50x magnification. Table IV contains the results of case depth measurements. Each root measurement satisfied the governing requirement. However, a case depth of 0.075 inch was measured from the damping ring groove sample, which exceeded the maximum allowable case depth. It was later learned that the masking was inadvertently omitted before the second carburization cycle by the subcontractor contributing to this excessive case depth.

Table IV
Case Depth Measurements
Vickers Microhardness Scale
500 gram load

Sample	Region	Case Depth (Inch)
1	Root	0.053
2	Root	0.049
3	Root	0.044
4	Damping Ring	0.075
	Requirement	0.030-0.050

X-Ray Diffraction

X-Ray diffraction was conducted by the primary contractor at two locations adjacent to the fracture origin. The results were consistent with typical residual stress profiles for shot-peened X-2M steel. X-Ray diffraction was utilized by ARL-MD to determine the amount of retained austenite within the structure of the failed part. The specification states that the maximum allowable amount of retained austenite shall be 20%. Two samples were analyzed, and results of 8.81 and 8.94% retained austenite were obtained. These values conformed to the governing specification.

Scanning Electron Microscopy/Energy Dispersive Spectroscopy

The extent of fatigue propagation observed on the fractured part was 1.65 inch followed by a ductile overload morphology. The fracture origin was located at a defect within the damping ring groove region. The defect was "half-moon" shaped and had a depth of approximatley 0.005 inch and a surface length of approximatley 0.015 inch. The defect had a darkened topogrpahy, and was considered evidence of a pre-existing crack opened to the surface during the manufacturing sequence of the gear.

Energy dispersive spectroscopy of the defect revealed the presence of sodium. This was evidence that the crack was open to the surface during the black oxide finish process. Sodium is typically found in the black oxide salts used by the subcontractor. Spectra obtained outside the darkened area contained no evidence of sodium.

Fractographic examination of a secondary through-fracture revealed an intergranular morphology within the case of the damping ring groove area (see Figure 6). The remaining morphology consisted of ductile dimples, indicative of overload fracture. No evidence of fatigue was noted in this section. This finding was evidence that a grinding crack had propagated along the continuous carbide networks.

Transmission Electron Microscopy/Striation Count

The contractor obtained two stage chrome/carbon replicas from the primary fracture surface of the failed gear. These replicas were examined utilizing the transmission electron microscope (TEM) to determine an approximate fatigue striation spacing. The fatigue striations were difficult to locate, as is the case with most high-strength alloys, and were only located in isolated regions on the fracture surface. Two regions were analyzed which exhibited measureable striations. These regions were approximately 0.50 inch and 1.05 inch from the fatigue origin, respectively. The average spacings are listed in Table V. The points were used to fit a standard crack growth curve, which assumed that fatigue cracks propagate at a much slower rate near the origin. Assuming one striation represented one load cycle, it was estimated the fatigue crack propagated from the origin to overload region in approximately 20,344,000 cycles. It should be noted that the striation spacing near the origin was unobtainable due to the magnitude of the spacings. The spacings, typically in the 10^{-9} inch range were beyond the resolution of both the replicating tape and the TEM.

Table V
Average Fatigue Striation Spacing
TEM

Sample Location	Average Spacing (Inch)
0.50 inch from origin	8.3×10^{-7}
1.05 inch from origin	3.5×10^{-6}

Conclusions

The primary fracture origin was located at a pre-existing processing defect, which was a half-moon shaped darkened region. This defect was determined to be a grinding crack which emanated from a grinding burn, and was considered a contributing factor to the failure of this component. The grinding crack/burn was characterized by an orientation perpendicular to the direction of grinding, a half-moon shape, a darkened, featureless topography, the presence of sodium in the darkened area, and a rehardened and retempered structure adjacent to the fracture origin. Although the morphology of the primary fracture origin (darkened area) was featureless, it was possible that the continuous carbide networks within the carburized case facilitated grinding crack propagation.

Figure 5 Metallographic cross-section through the damping ring groove region which was double carburized inadvertently. Note the carbide networks in the carburized case formed by this excess carbon. Mag. 300x.

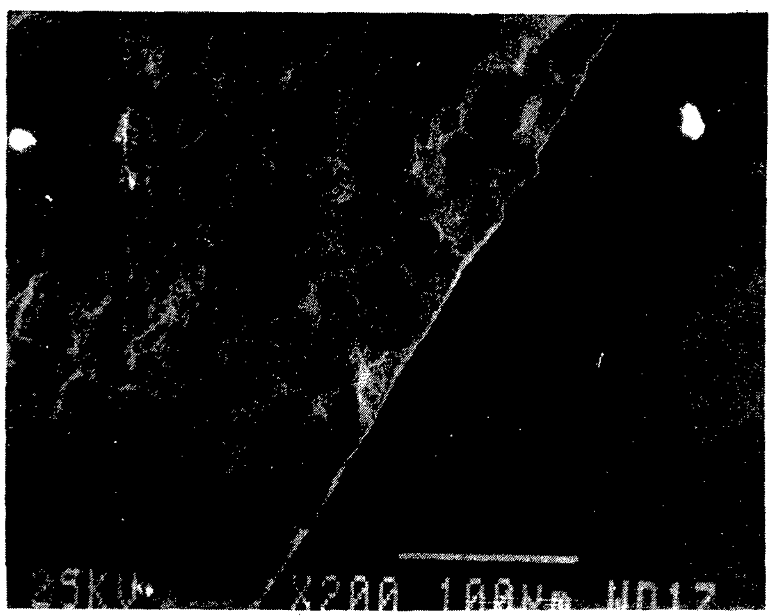

Figure 6 Secondary fracture sample from the damping ring groove area found to contain an intergranular morphology. A grinding crack most likely propagated along the carbide networks. Mag. 200x.

Corrective Measures

This failure was the second spiral bevel transmission gear to fail in three years. The first failure occurred when a 9-tooth segment of the gear fractured. Although major fire damage made that investigation difficult, it was determined that a fatigue crack had grown before final fracture. The origin of that failure was also determined to be the damping groove region. Steps were taken by the contractor to ensure this type of failure would not recur, including an additional magnetic particle inspection in the manufacturing process. In addition, grinding in the damping ring groove has been eliminated and replaced with a turning procedure which should keep heat generation to a minimum and ensure that defects related to grinding will not occur. In addition, a nital etch with 10x magnification step has been added to the inspection process, which should also help to detect future defects. The contractor has also agreed to consider an addition to the material specification which would consist of micrographs of unacceptable case microstructures. This would aid the subcontractor in determining rejectable parts before they are placed into service.

References

[1] American Society for Metals (ASM) Handbook, Volume 8, Mechanical Testing, "Rockwell Hardness Testing", p. 75, 1992.